VLA IMAGING OF PROTOPLANETARY ENVIRONMENTS

Grant NAG5-8195

Final Report

For the period 1 February 1999 through 31 January 2004

Principal Investigator

Dr. David J. Wilner

April 2004

Prepared for

National Aeronautics and Space Administration
Goddard Space Flight Center, Greenbelt, MD

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

April 23, 2004

Final Report – Grant NAG5-8195

P.I. David J. Wilner

We summarize the major accomplishments of our program to use high angular resolution observations at millimeter wavelengths to probe the structure of protoplanetary disks in nearby regions of star formation. The primary facilities used in this work were the Very Large Array (VLA) of the National Radio Astronomy Observatories (NRAO) located in New Mexico, and the recently upgraded Australia Telescope Compact Array (ATCA), located in Australia (to access sources in the far southern sky). We used these facilities to image thermal emission from dust particles in disks at long millimeter wavelengths, where the emission is optically thin and probes the full disk volume, including the inner regions of planet formation that remain opaque at shorter wavelengths. The best resolution obtained with the VLA is comparable to the size scales of the orbits of giant planets in our Solar System (< 10 AU).

1. PPIV Review Article on Disks

We wrote an extensive review article titled "Subarcsecond Millimeter and Submillimeter Observations of Circumstellar Disks" for the book *Protostars and Planets IV*, the latest volume in a series that has become the primary reference in the field. This review develops the astrophysical motivations for aperture synthesis millimeter observations of protoplanetary disks, and describes in detail the well-studied young stellar objects HL Tau and L1551 IRS5 in order to illustrate what information may be obtained using this technique [**1**].

2. Fast-Switching Phase Calibration for High Angular Resolution

An important issue at millimeter wavelengths is atmospheric phase fluctuations that can limit angular resolution in interferometer observations. We have further developed and tested the method of fast-switching phase calibration that enables subarcsecond imaging. This method is essential for imaging dust emission from disks around young stars at the highest resolution available to the VLA and millimeter interferometers [**2**].

3. The TW Hydra Disk: Observations and Analysis

We proposed for and obtained VLA 7 mm observations of the dust in the TW Hya system, a remarkable isolated 10 Myr old star similar to the young Sun, and we published thorough analyses of these data [**3,4**]. The TW Hya system is unique in that it is located two and a half times closer than the disks around stars associated with the closest dark clouds, and therefore allows for maximum linear resolution. This work required preliminary observations to determine the best calibrators for phase referencing. The main result is that the 7 mm emission is dominated by a dusty disk of radius > 50 AU. The dust spectrum and spatially resolved 7 mm images of the TW Hya disk can be fitted by a simple model with temperature and surface density described by radial power laws, $T(r) \propto r^{-0.5}$ and $\Sigma(r) \propto r^{-1}$, consistent with an irradiated gaseous accretion disk of mass ~ 0.03 $M_\odot$ with an accretion rate $\sim 10^{-8}$ $M_\odot$ yr^{-1} and viscosity parameter $\alpha = 0.01$. The estimates of mass and mass accretion rates are uncertain as the gas-to-dust ratio in the TW Hya disk may have evolved from the standard interstellar value. The observations provide hints of substructure within the disk, but data with much better sensitivity will be required to confirm the reality of these features.

4. The TW Hydra Disk: More Detailed Theoretical Treatment

We subsequently made a very detailed theoretical treatment of the TW Hya disk that incorporates the VLA 7 mm observations [**5**]. The model requires a clearing of disk material within a few AU of star, possibly due to the formation of a planet, and also substantial growth of the dust particles in the disk towards planetesimals. Figure 1 shows a comparison of the 7 mm data with the detailed radiative transfer model of the disk. The good agreement confirms the utility of our earlier parametric modeling using radial power laws for the temperature and surface density. The new model is constructed from first principles, however, by solving the disk structure equations in the presence of stellar irradiation subject to the constraint of steady accretion, and we are able to predict and confirm not only the radial dependences of the physical quantities, which are not exactly power laws, but also their absolute values.

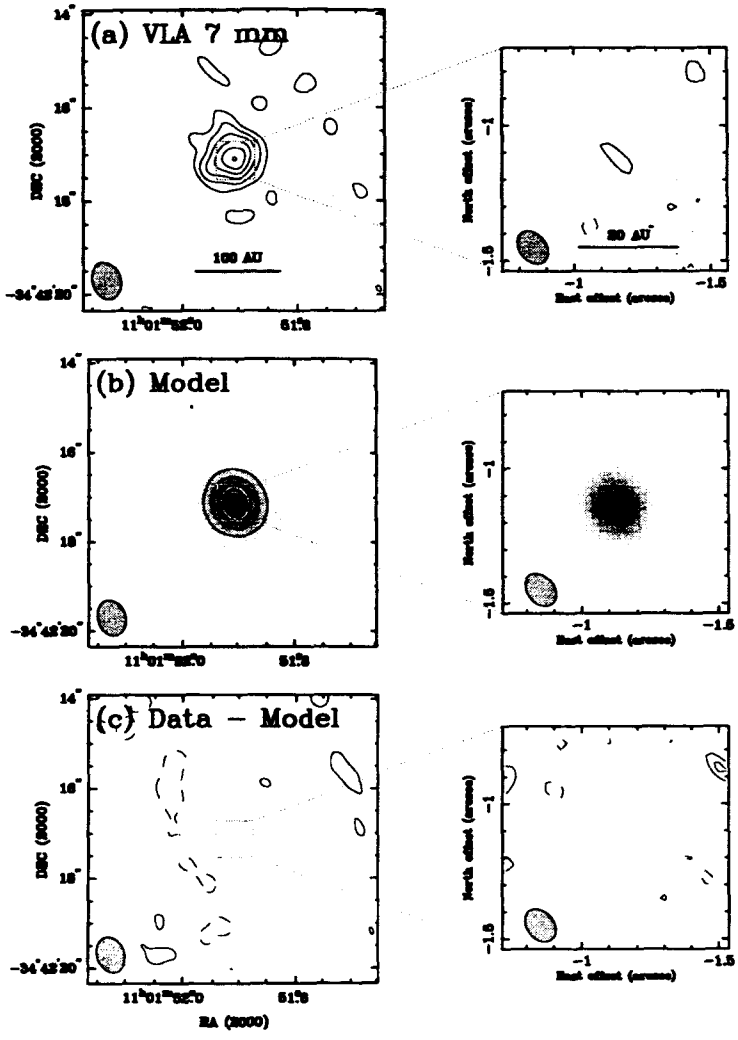

Fig. 1.— Comparison of VLA 7 mm images of TW Hya and a detailed radiative transfer model of an irradiated accretion disk: (a) VLA 7 mm images of TW Hya at two resolutions. The synthesized beam sizes are $0\farcs82 \times 0\farcs61$, P.A. = 20 (left) and $0\farcs13 \times 0\farcs10$, P.A. = 39 (right). The contour levels are (2, 3, 4, 5, 6) × the rms noise levels of 0.5 and 0.4 mJy beam^{-1}. Negative contours are dashed. (b) Synthetic VLA 7 mm images of the disk model brightness distribution. The contours and beam sizes are the same as in (a). The gray-scale shows extended emission, most of which remains undetectable with the available VLA sensitivity. (c) Difference images obtained by subtracting visibilities derived from the model from the VLA 7 mm data. The residuals show no significant signal.

5. Highest Resolution VLA 7 mm Disk Observations

We proposed for and successfully obtained VLA 7 mm A configuration data on three disk systems in the Taurus dark cloud. These observations made use of newly outfitted antennas with 7 mm receivers. Despite unfavorable weather conditions for most of our scheduled time, resulted in images with the best 7 mm sensitivity and resolution achieved to date. All three disk sources showed detectable 7 mm emission, directly probing the planet forming zone of the circumstellar environment. We successfully obtained follow up observations of one of these sources, DG Tau, making the first VLA 7 mm astronomical observations with the optical fiber link from the VLA to the Pie Town antenna of the VLBA. The VLA-Pie Town link effectively doubles the angular resolution.

Figure 2 shows the results for DG Tau, which was the most interesting system observed, with images made at two resolutions, about 55 mas and 35 mas (5 AU). The lower resolution image clearly shows the inner part of the dusty disk, extended perpendicular to the direction of the optical jet indicated by the arrow. The ellipses to the right show the scale of the orbits of the giant planets in our Solar System. The higher resolution image shows only the higher brightness emission, with a very interesting asymmetry whose origin is unclear but may be related to the outflow, to the condensation of a protoplanet from the disk, or perhaps to the dynamical effect of an already formed protoplanet. It is possible that a fraction of the emission in the higher resolution image comes from ionized gas and not dust. Since the dynamical timescales at this scale are short for either orbital motion or outflow (years), we will be able to discriminate among some of the many possibilities for the structure with a second epoch image.

These results were described in an invited contribution to the ESO Workshop on *The Origins of Stars and Planets* in April, 2001 [**6**].

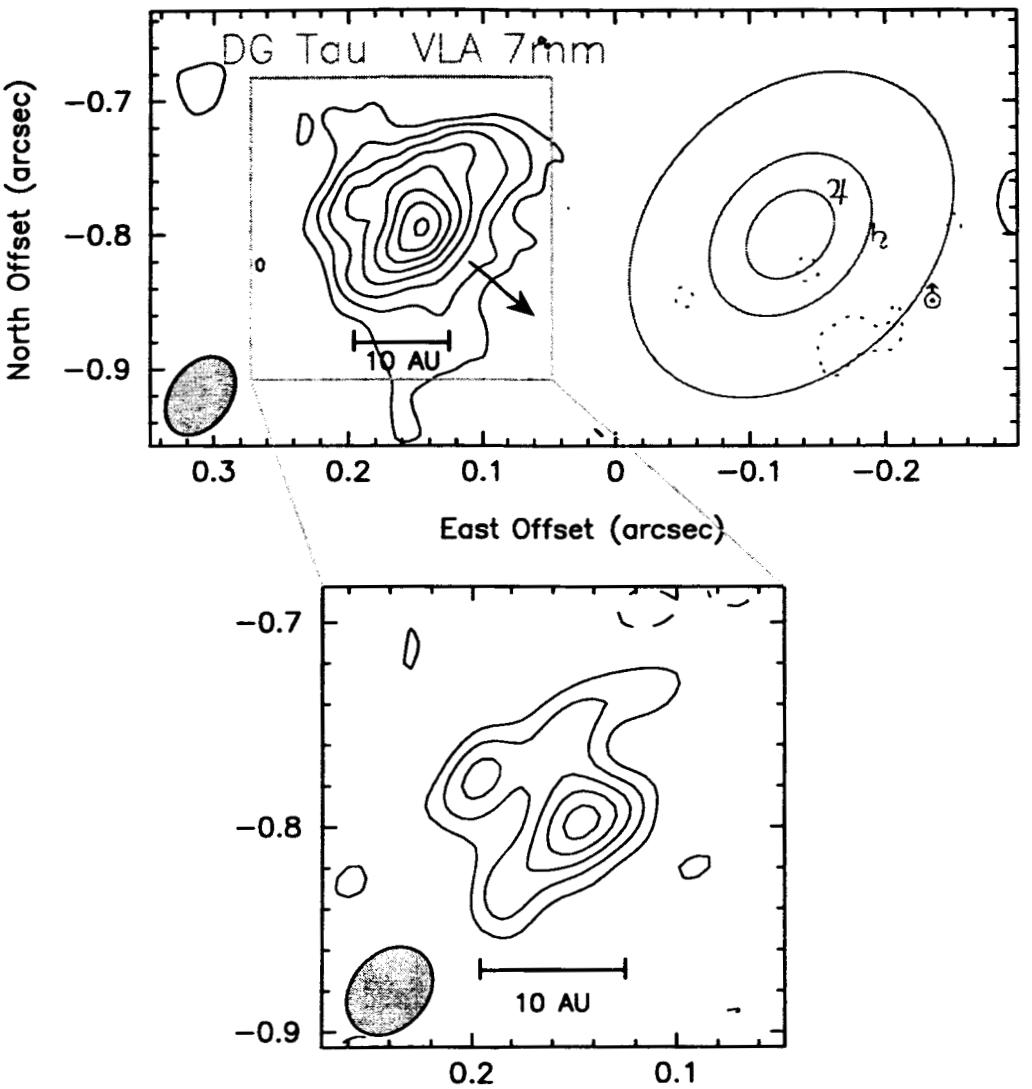

Fig. 2.— VLA & VLBA Pie-Town link 7 mm continuum images of the DG Tau system at two angular resolutions. The upper panel shows the inner part of the dust disk; the arrow indicates the position angle of the optical jet observed at larger scales. The ellipses to the right show the orientation of the disk, and the spacings of the ellipses correspond to orbits of the giant planet orbits in our Solar System. Contours levels are $(2, 3, ...) \times 0.12$ mJy (upper) and 0.14 mJy (lower). The synthesized beam size in the higher resolution image is ~ 35 mas (5 AU at 140 pc distance).

6. The CQ Tauri Disk: Observations and Analysis

We proposed for and obtained VLA 7 mm data on the 10 Myr old, 1.5 $M_\odot$ pre-main-sequence star CQ Tau and published papers on grain growth in the disk [7] and on the spatially resolved structure of the disk [8]. Much of the effort in this work involved improving the modeling, e.g. developing a more accurate scheme to compute disk flaring and more realistic dust prescriptions for the disk midplane and surface. Figure 3 shows the subarcsecond 7 mm observations of CQ Tau that resolve the disk. We interpret the fluxes from 7 to 1.3 mm, together with the resolved 7 mm structure, and find that the disk radius is constrained to the range 100 to 300 AU, depending on the steepness of the surface density distribution, which is likely close to r^{-1}, and that the power law index of the dust opacity coefficient, β, is constrained to be 0.5 to 0.7. Since the models indicate that the disk is optically thin at millimeter wavelengths for $r > 8$ AU, the contribution of an optically thick region to the emission is insignificant. This implies that high optical depth or complex disk geometry cannot be the cause of the shallowness of the millimeter spectral index. Instead, the analysis supports the earlier suggestion that dust particles in the disk have grown to sizes of a millimeter or more. The dust in the CQ Tau system appears to be evolved much like that in the TW Hya system.

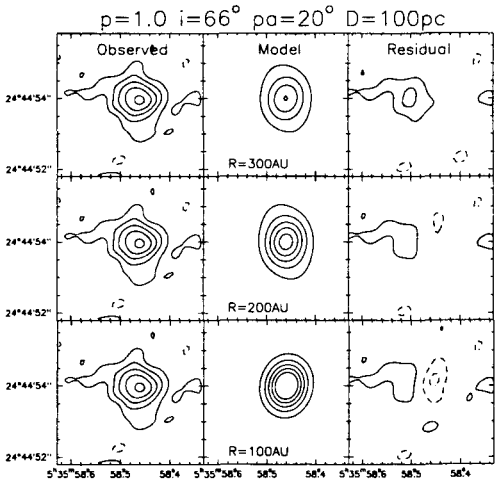

Fig. 3.— Comparison between observed and synthetic 7 mm images of the CQ Tau disk. The observed image is shown in the left panels, with contour levels starting at 0.2 mJy and spaced by 0.2 mJy (2σ). The models in the central panels show three different values of the disk radius; the surface density power law index (p=1.0), inclination (i= 66 degrees) and position angle (20 degrees) are the same for all models shown. The right panels show the residuals after subtraction of the model. These models, together with the flux constraints, confirm that the millimeter emission originates from an optically thin disk with a population of large grains.

7. Far Southern Disks: First Observations and Analysis

We proposed for an obtained the first millimeter interferometer observations of protoplanetary disks in the southern hemisphere, where there are many very interesting sources that are difficult or impossible to observe with the VLA, using the newly upgraded ATCA [9]. The first results at 3.4 mm wavelength using only three antennas were very encouraging: we detected compact thermal dust continuum emission from two systems, the disks surrounding HD 100546 and TW Hya (again). For TW Hya, we also detected and resolved HCO^+ J=1–0 line emission from the disk, with properties in good agreement with model calculations that include substantial molecular depletions. These results were prominently featured in a cover story of the ATCA Newsletter, as well as the Australia Telescope National Facility 2002 Annual Report. Prompted by the success of these first observations, we obtained data on a sample of about ten additional stars using the ATCA to identify additional interesting systems. At least two of these are sufficiently well detected to attempt future studies with higher angular resolution, a capability expected to become available with the ATCA in the next year.

8. Highlights Presented at IAU Symposium 221

Several highlights of our program were presented in an invited review on "High Angular Resolution Studies of Disks– the Millimetre" at IAU Symposium 221, *Star Formation at High Angular Resolution*, at the IAU General Assembly in July, 2003 [10].

9. Ongoing High Resolution Millimeter Observations of Disks

We continue to make progress obtaining and analyzing high angular resolution millimeter observations of disks around nearby pre-main-sequence stars with support from a subsequent grant from the Origins of Solar Systems Program, building on the observations and analysis tools developed in the investigations described. In particular, we obtained new low resolution VLA observations of the disks around T Tauri stars and Herbig Ae/Be stars, some of which repeat observations made in the earliest days of this grant, now that the VLA 7 mm system is more mature and much more sensitive. We are also attempting follow-up observations of the most promising sources with the ATCA. The resolved millimeter data allow exploration of the physics of disk accretion, grain growth, and the initial conditions for planet formation.

Major Publications supported by NAG5-8195

1. **Wilner, D.J.**, Lay, O.P. 2000, "Subarcsecond Millimeter and Submillimeter Observations of Circumstellar Disks", in *Protostars and Planets IV*, eds. V. Mannings, A. Boss and S. Russell (Tucson: University of Arizona Press), p. 519

2. Morita, K.-I., Handa, K., Asaki, Y., Kitamura, Y., Yokogawa, S., Kamazaki, T., Saito, M., **Wilner, D.J.**, Ho, P.T.P., Ohashi, N. 2000, "Fast Switching Experiments with the Nobeyama Millimeter Array" in Imaging at Radio through Submillimeter Wavelengths, ed. J. Mangum, (San Francisco: ASP), p. 340

3. **Wilner, D.J.**, Ho, P.T.P., Kastner, J.H. and Rodriguez, L.F. 2000, "VLA Imaging of the Disk Surrounding the Nearby Young Star TW Hya", *The Astrophysical Journal*, **534**, L101

4. **Wilner, D.J.** 2001, "Millimeter Observations of the TW Hya System", in Young Stars Near Earth: Progress and Prospects, eds. R. Jayawardhana and T. Greene, (San Francisco: ASP), p. 191

5. Calvet, N., D'Alessio, P., Hartmann, L., **Wilner, D.**, Walsh, A. and Sitko, M. 2002, "Evidence for a Developing Gap in a 10 Myr old Protoplanetary Disk", *The Astrophysical Journal*, **568**, 1008

6. **Wilner, D.J.** 2002, "VLA Studies of Disks around T Tauri Stars", Springer-Verlag series of ESO Astrophysics Symposia, eds. J. Alves and M.J. McCaughrean, p. 311

7. Testi, L., Natta, A., Shepherd, D.S., **Wilner, D.J.** 2001, "Constraints on Properties of the Protoplanetary Disks around UX Ori and CQ Tau", *The Astrophysical Journal*, **554**, 1087

8. Testi, L., Natta, A., Shepherd, D.S. **Wilner, D.J.** 2003, "Large Grains in the disk of CQ Tau", *Astronomy and Astrophysics*, **403**, 323

9. **Wilner, D.J.**, Bourke, T.L., Wright, C.M., Jorgensen, J.K., van Dishoek, E.F., and Wong, T. 2003, "Disks around the Young Stars TW Hya and HD 100546 Imaged at 3.4 Millimeters with the Australia Telescope Compact Array", *The Astrophysical Journal*, **596**, 597

10. **Wilner, D.J.** 2004, "High Angular Resolution Studies of Disks– the Millimetre" in *Star Formation at High Angular Resolution*, proceedings of IAU Symposium 221, eds. Michael Burton, Ray Jayawardhana and Tyler Bourke, (San Francisco: ASP), in press

---

This final report was prepared with the AAS LaTeX macros v4.0.